WAFIRS, A WAVEGUIDE FAR-IR SPECTROMETER: ENABLING SPACE-BORNE SPECTROSCOPY OF HIGH-Z GALAXIES IN THE FAR-IR AND SUBMM

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ABSTRACT

The discovery of galaxies beyond z~1 which emit the bulk of their luminosity at long wavelengths has demonstrated the need for high-sensitivity, broadband spectroscopy in the far-IR/submm/mm bands. Because many of these sources are not detectable in the optical, long-wavelength spectroscopy is key to measuring their redshifts and ISM conditions. The continuum source list will increase in the next decade with new ground-based instruments (SCUBA2, Bolocam, MAMBO) and the surveys of HSO and SIRTF. Yet the planned spectroscopic capabilities lag behind, primarily due to the difficulty in scaling existing IR spectrograph designs to longer wavelengths.

To overcome these limitations, we are developing WaFIRS, a novel concept for long-wavelength spectroscopy which utilizes a parallel-plate waveguide and a curved diffraction grating. WaFIRS provides the large (~60%) instantaneous bandwidth and high throughput of a conventional grating system, but offers a dramatic reduction in volume and mass. WaFIRS requires no space overheads for extra optical elements beyond the diffraction grating itself, and is two-dimensional because the propagation is confined between two parallel plates. Thus several modules could be stacked to multiplex either spatially or in different frequency bands. The size and mass savings provide opportunities for spectroscopy from space-borne observatories which would be impractical with conventional spectrographs. With background-limited detectors and a cooled 3.5 telescope, the line sensitivity would be better than that of ALMA, with instantaneous broad-band coverage. We have built and tested a WaFIRS prototype for 1-1.6 mm, and are currently constructing Z-Spec, a 100 mK model to be used as a ground-based $\lambda/\Delta\lambda$~350 submillimeter galaxy redshift machine.

SCIENTIFIC MOTIVATION

The advent of large-format bolometer arrays for wavelengths around 1 mm (SCUBA, MAMBO) had revealed a new class of galaxies which are likely at medium to high redshift. These sources are cosmologically significant – their counts reproduce much of the diffuse far-IR / submillimeter background radiation, representing the energy generated by all galaxies over the history of the universe[1,2]. These submillimeter galaxies are luminous systems similar to the nearby IR galaxies discovered with IRAS. Of the nearly 200 submillimeter galaxies discovered thus far, only a small fraction have confirmed spectroscopic redshifts and well-determined properties at other wavelengths. This is because the sources are very dusty with high extinction at short wavelengths, the optical and UV energy is almost entirely reprocessed and reradiated between $\lambda = 50$ μm and 1 mm, making the optical counterparts too faint to be detectable. While there are spectral features that could be used in the millimeter / submillimeter, the instantaneous bandwidth of heterodyne millimeter-wave receivers is currently a small fraction of unity, so

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searching for lines in sources with unknown redshifts is impractical. The long-wavelength continuum source list will only increase in the next decade with new ground-based instruments (SCUBA2, Bolocam) and the confusion-limited surveys of HSO and SIRTF. The recently discovered submillimeter galaxies, and their soon-to-be-discovered far-IR cousins demonstrate the need for broad-band spectroscopy in the far-IR / submillimeter / millimeter bands. Long wavelength spectroscopy with large instantaneous bandwidth is the key to measuring these sources' redshifts, which constrain their luminosities, sizes, and masses. Moreover, the wide variety of spectral features in the mid- and far-IR provide information on the conditions in the interstellar medium and contrain the luminosity source(s).

SENSITIVITY FROM SPACE

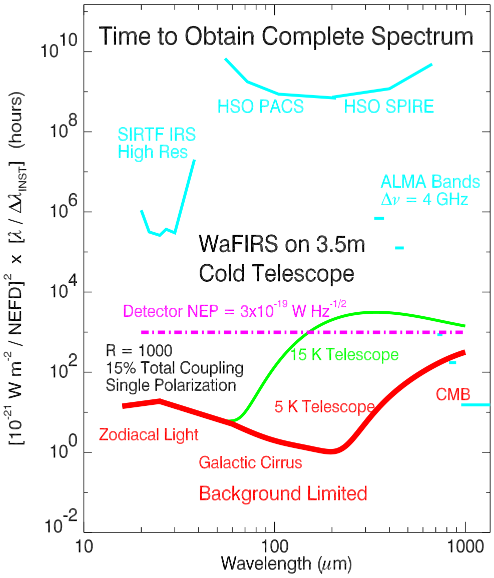

Figure 1 *Sensitivity of a background-limited spectrometer on a cold telescope, including the effect of instrumental bandwidth on line survey speed.*

In spite of the wealth of spectral diagnostics, the far-IR / submmm regime is not generally accessible from the ground. While there are space missions planned to observe these wavelengths in the continuum (SIRTF, HSO), there is very limited spectroscopic capability planned for these wavelengths from space. The sensitivity attainable from a modest (diameter ~ 3.5 m) cool (T < 15 K) space telescope is dramatically better than what is currently planned between SIRTF and ALMA. The effective line survey speed, proportional to the inverse of the sensitivity squared divided by the instantaneous bandwidth shows a more dramatic gain of several orders of magnitude (see Figure 2). These large potential gains are possible in part because the raw sensitivity improves substantially by cooling the telescope to 15 K or lower (HSO is expected to operate at about 60 K). Another key aspect for observing sources with unknown redshifts is that the spectrometers on HSO are not optimized for line surveys. PACS is an imaging spectrometer with only a 1% instantaneous bandwidth, and SPIRE is a Fourier transform instrument with noise from the full band on the detectors at once. For an 8 meter class cold telescope such as SAFaIR, the sensitivity advantages are improved an additional factor of more than 5 beyond what is plotted in Figure 1.

TECHNICAL BACKGROUND: WHY A WAVEGUIDE SPECTROMETER

While there are a variety of options for a far-IR and submillimeter spectrometer, some are better suited to the science goals outlined above – observing high-redshift dusty galaxies with high sensitivity. Sources will be taken from preceeding continuum surveys, and will be spatially unresolved, so that imaging is not particularly important. In most cases, the redshifts will not be known in advance and the diagnostic lines are distributed over a broad spectral range, so a large instantaneous spectral bandwidth is critical. Given that in the far-IR and submillimeter, the total number of detectors is typically a constraint, it therefore desirable to have the detectors arrayed spectrally rather than spatially, and an imaging monochromator such as a Fabry-Perot is not the instrument of choice. For ultimate sensitivity, a Fourier transform spectrometer (FTS) is not ideal because it places the entire spectral bandwidth and its associated photon noise onto a single detector. The obvious choice for background-limited point-source spectroscopy is a diffraction grating. When operated in first order, a grating naturally provides an octave of instantaneous bandwidth, and the resolution can be increased by increasing the grating size, roughly d ~ λ x R/2. At far-IR and submillimeter wavelengths, this size quickly becomes prohibitively large, especially since real instruments are typically larger than the fundamental limit because they include collimating and imaging mirrors as well as order-sorting elements. For example, each of the spectrometer modules on SIRTF, measures about 40 x 15 x 20 cm, with a maximum λ x R product of 2 cm (R = 600 at 37 μm). To scale such an instrument up for a wavelength of 200 µm would result in a long dimension of over 2 meters, prohibitive for a space mission. The sizes of existing spectrometers are shown in Figure 2 in units of λ^3, plotted against the total number of spectral resolution elements.

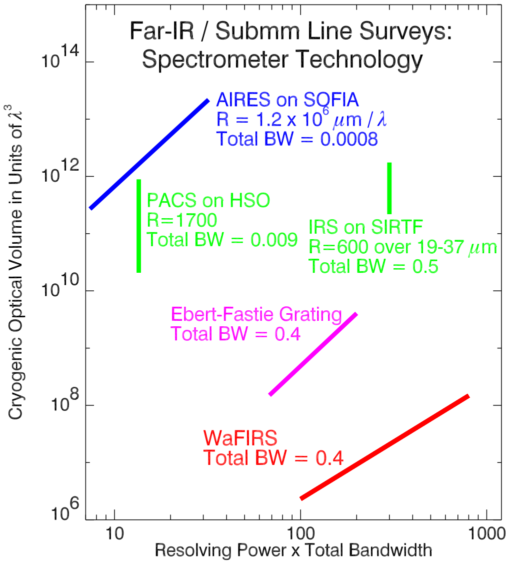

Figure 2. *Sizes of existing spectrometer modules compared with their survey capability. The spectral survey capability of an instrument is given by its resolving power X total bandwidth. Modest resolution, broad-bandwidth systems exist (eg the SIRTF IRS modules) but are prohibitively large when scaled to far-IR and submm wavelengths. WaFIRS offer a compact broadband system for longer wavelengths.*

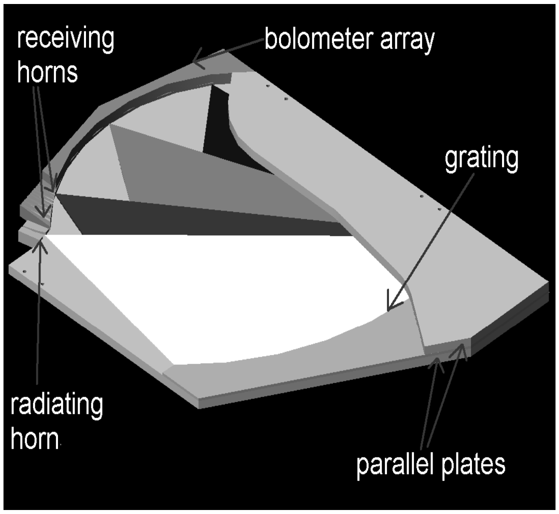

***Figure 3**. WaFIRS spectrometer concept.*

WaFIRS, the Waveguide Far-IR Spectrometer, is a dramatically more compact system. It consists of a curved diffraction grating, entrance feed horn and detector feed horns all inside a parallel-plate propagation medium (see Fig 3). The spectrometer need be only a few wavelengths thick due to the two-dimensional geometry. Several spectrometers could easily be stacked to provide multiple wavelength bands, multiple spatial pixels, or both. The curved diffraction grating is the most space-efficient grating configuration possible because it both disperses and focuses the light. The grating can be nearly as large as the largest spectrometer dimension, with very little overhead, thus providing the maximum resolving power for a given cryogenic volume. Furthermore, the grating is used in first order which provides up to an octave of instantaneous bandwidth for any given module. The design has no moving parts and, once assembled, is completely light tight. The compact, lightweight geometry and robust construction make WaFIRS extremely well-suited for airborne, ballon and space-based spectroscopy.

WAFIRS TECHNICAL DISCUSSION

WaFIRS is conceptually similar to the slit spectrometers with curved gratings used by Rowland, Wadsworth, Eagle and others[3]. Though WaFIRS uses the same basic layout, it is based on propagation of a single electromagnetic mode in a two-dimensional medium bounded by parallel, conducting plates. Light is injected into a WaFIRS module with a horn which provides a suitable illumination pattern on the grating. The grating is in first order, and diffracts the light to a circular focal curve which extends over nearly 90 degrees of arc, on which the feed-horn coupled bolometers are arrayed. Figure 3 shows a sketch of the WaFIRS concept.

We have designed and built a prototype for wavelengths of 1-1.6 mm. The spectral resolving power is between 180-250 and the overall size only 56 cm x 42 cm x 2.5 cm. The key to the design is the placement of each facet individually such that for two frequencies, the change in propagation phase from the input to the output is exactly 2π between two adjacent facets, providing perfect (stigmatic) performance at these two frequencies. In this prototype, there are 400 facets, and the resulting grating curve has a length of 51 cm. To evaluate the spectrometer designs, we perform diffraction calculations which account for the

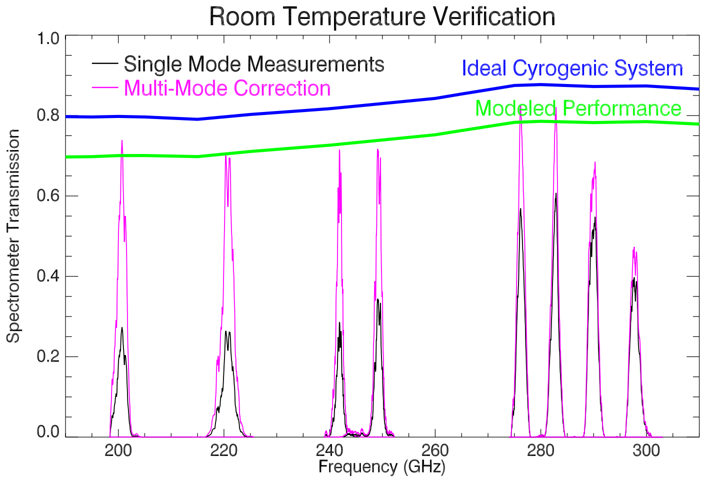

***Figure 4**. Testing of the first WaFIRS prototype. Measurements were made with a detector behind a single-mode feed, which does not couple all the power in the profile. Accounting for this coupling inefficiency produces the corrected curves which are close to performance predicted by the waveguide propagation loss and spillover loss. Resolving powers are close to predicted.*

amplitude and phase produced by the input horn at each facet, then sum the contributions from all the facets at each output location. Because the facet positions are individually calculated, the geometric aberrations are completely negligible, and the system is strongly diffraction limited. Estimates of the spectrometer efficiency must include losses from: 1) Waveguide propagation with finite-conductivity plates, 2) diffraction efficiency into the proper order (i.e. blaze efficiency), and 3) illumination losses. Figure 4 plots our calculations of these contributions, and their product along with our measurements with a single-mode detector. The waveguide propagation loss is given by standard expressions[4], the 3 % loss for total propagation from input to detector can be achieved by polishing and gold-plating the parallel plates. In our prototype operated with only nickel coated plates and an aluminum grating, the propagation efficiency is somewhat lower. The blaze efficiency is calculated with commercially available software, applicable since with the waveguide propagation mode, the radiation is effectively in TE grating mode. The measured results are quite close to our predictions over much of the band. We are investigating the reason for the loss in performance at the highest frequencies, it is likely a blaze efficiency.

SCALABILITY: MM GROUND BASED AND FAR-IR MODULES

In addition to our λ=1 mm prototype, we are constructing a cyrogenic version, Z-Spec for observations from ground-based submillimeter / millimeter observatories. Z-Spec will demonstrate the capability of WaFIRS to provide broadband spectroscopy with background-limited sensitivity. We have produced designs with the same size and shape for a variety of shorter wavelengths, including a system which provides R=2000 at λ=100 μm. As wavelength is shortened, the number of facets and spectral resolution elements increases while the facet size and the physical size of a resolution element decrease. The grating remains in first order and the total instantaneous bandwidth is maintained. The extension to shorter wavelengths is possible because the design produces a stigmatic geometry for the grating, and geometric aberrations are small.

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